

Development of Algorithms and Strategies for Monitoring Chlorophyll and Primary Productivity in Coastal Ocean, Estuarine and Inland Water Ecosystems

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Summary

This is the final technical report for the Execution Phase of my MODIS Instrument Team investigator project which began in June 1997. This report summarizes the work accomplished under this contract, and includes specific accomplishments for the period July through December 2003 that have not appeared in previous reports. The objectives of this work were:

- Establish a protocol for developing regional or site-specific bio-optical algorithms for coastal “case 2” waters.
- Prescribe a protocol for “stitching together” local or site-specific algorithms.
- Demonstrate these protocols in two coastal seas: the Gulf of Maine/Mid-Atlantic region, and the Yellow Sea/East China Sea region.
- Develop a strategy for monitoring coastal oceans, estuaries, and inland waters.

This report reflects the efforts of a research team consisting of myself, two scientists (Dr. Mark Dowell and Timothy Moore), and one Ph.D. student (Seung-Hyun Son). A list of papers published, in press, or submitted, and presentations related to this work is provided as an appendix to this report.

Case 2 Algorithm Protocol Development

There are two areas of algorithm development that were addressed in this project. One was the bio-optical algorithm that retrieves chlorophyll and other optically-active constituent concentrations. The second area was the primary productivity algorithm.

• Bio-optical algorithms

As one of several new MODIS Science Team members selected in 1996, my MODIS team investigation, entitled “Development of Algorithms and Strategies for Monitoring Chlorophyll and Primary Productivity in Coastal, Estuarine, and Inland Waters,” did not call for the creation of a new algorithm or ATBD. I advocated an approach for coastal (“Case 2”) waters whereby regionally tuned algorithms, similar to the semi-analytical algorithm of Kendall Carder, would be blended to produce global products (Moore *et al.* 2001). This approach would allow the differentiation of several bio-optical provinces (not just Case 1 vs. Case 2), and could form the basis for a unified chlorophyll algorithm. This approach will be described in greater detail in a later section.

After the launch of Terra, I participated in the evaluation of the MODIS chlorophyll and water-leaving radiance products, often comparing them with SeaWiFS data. It seemed obvious that MODIS should produce a chlorophyll product as consistent as possible with the SeaWiFS chlorophyll. It was not feasible to introduce a new product into the MODIS data processing stream at that stage, but there was one orphan product, *chlora_2*, that had received little attention to date which could be adopted for this purpose. Initially, it was being generated with a two-band algorithm involving the ratio of reflectances at 488 to 551 nm, which was essentially the at-launch SeaWiFS chlorophyll algorithm, called OC2 (O'Reilly *et al.* 1998). A more recent, improved version of this algorithm (OC2.v2) had been developed and documented, along with improved versions of a three-band algorithm (OC3M) proposed for MODIS, and a four-band algorithm (OC4.v4) proposed for SeaWiFS (O'Reilly *et al.* 2000).

The SeaWiFS-analog chlorophyll algorithm

To prescribe a SeaWiFS-analog chlorophyll algorithm for MODIS, I first evaluated several candidate algorithms, including OC2.v2 and OC3M. I also considered using the OC4.v4 algorithm without the 510 nm band. The algorithms were first tested with *in situ* reflectance data to see how they performed against measured chlorophyll, and then a series of intercomparisons were made with satellite data. Based on this analysis, I recommended adoption of the OC3M algorithm:

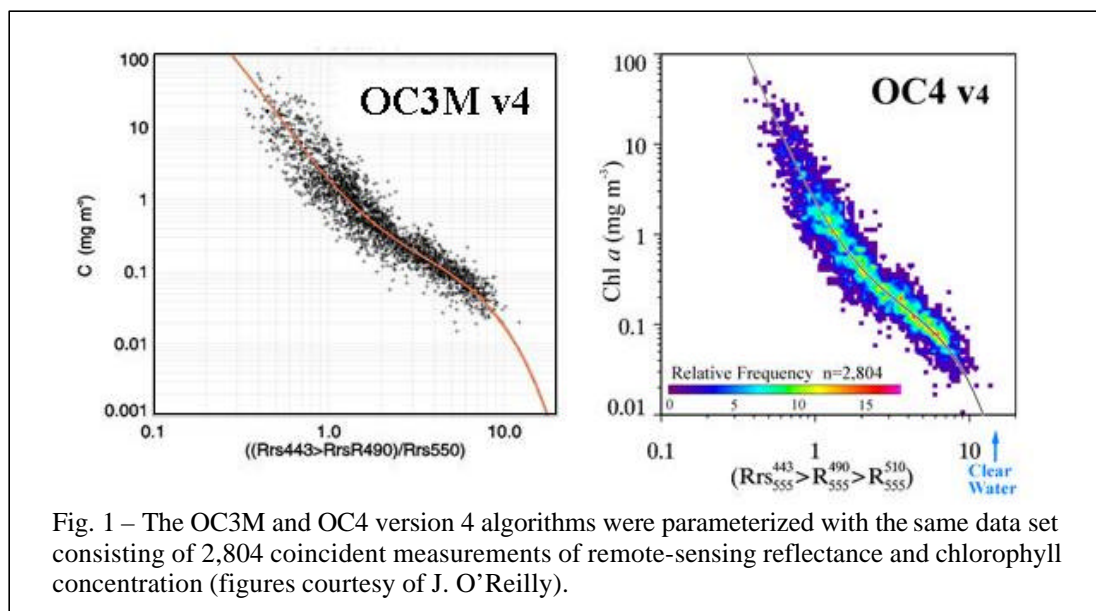
$$\log_{10}(\text{CHL}) = 0.283 - 2.753X + 1.457X^2 + 0.659X^3 - 1.403X^4 \quad (1)$$

where

$$X = \log_{10}[\max[R_{rs}(443), R_{rs}(488)] / R_{rs}(551)] \quad (2)$$

The 443-551 ratio is always the maximum in low-chlorophyll (blue) waters, but as the chlorophyll concentration increases, reflectance in the 443-nm band diminishes due to the strong absorption of chlorophyll (and other organic matter). Eventually, the 488-551 ratio becomes the larger ratio. The form of this algorithm is similar to the OC4 algorithm, in that it uses a maximum reflectance ratio, but the OC4 also uses a third ratio involving the 510 nm band, which MODIS does not have.

The original report describing the OC4.v4 algorithm (O'Reilly *et al.* 2000) summarized the accuracy of that algorithm. When regressed against 2,804 measured chlorophyll values (in log-log space, Fig. 1), the OC4 regression had an $r^2 = 0.89$, slope = 1, intercept = 0, RMS error = 0.22, and bias = 0.000 (the last 4 values are decades of log). This same report gave the parameters of the OC3M algorithm but no statistics regarding its accuracy. To prescribe a level of accuracy for the OC3M algorithm, I evaluated this algorithm and the OC4.v4 using both *in situ* data and an intercomparison of near-coincident SeaWiFS and MODIS data.



• *In situ Data Results.* We assembled a data set consisting of chlorophyll and spectral reflectance measurements made at 1,119 stations. All the data were obtained from the SeaBASS archive maintained by the NASA SeaWiFS and SIMBIOS Projects. The data were from four sources: (1) a subset of the original SeaBAM data (O'Reilly *et al.*, 1998) which had measurements at 443, 490, and 510 nm ($n = 539$); (2) Atlantic Meridional Transect (AMT) data from cruises 5-8 ($n = 366$; provided by S. Hooker); (3) data from ECOHAB cruises to the West Florida Shelf from Sept. 1999 through Sept. 2001 ($n = 133$; provided by K. Carder); and (4) data from the TIES campaigns (Aug. 1996, May 1997, and Aug. 1997) in the Chesapeake Bay ($n=81$; provided by L. Harding). Various algorithms were applied to these data to derive chlorophyll estimates, and results were regressed against the measured chlorophyll (on log-log scales). The results for OC3M and OC4.v4 are shown in figure 2 and summarized in Table 1.

Table 1. - Regression Statistics for Comparisons of Algorithms with *In situ* Chlorophyll

log(OC3M Chl) vs. log(measured Chl)							
Data Set	n	Chl range	slope	intercept	r^2	RMS	Bias
SeaBAM	539	0.025 - 32.8	0.938	-0.113	0.924	0.184	-0.079
AMT	366	0.023 - 8.3	0.880	-0.194	0.839	0.256	-0.133
W. Fla Shelf	133	0.088 - 5.9	1.149	0.072	0.912	0.175	0.008
Chesapeake	81	2.50 - 61.8	0.667	1.008	0.183	0.787	0.685
All Data	1119	0.023 - 61.8	1.128	0.022	0.880	0.293	-0.031
log(OC4.v4 Chl) vs. log(measured Chl)							
Data Set	n	Chl range	slope	intercept	r^2	RMS	Bias
SeaBAM	539	0.025 - 32.8	0.909	-0.081	0.930	0.163	-0.031
AMT	366	0.023 - 8.30	0.837	-0.172	0.844	0.231	-0.089
W. Fla Shelf	133	0.088 - 5.9	1.119	0.097	0.912	0.172	0.046
Chesapeake	81	2.50 - 61.8	0.645	0.808	0.225	0.572	0.464
All Data	1119	0.023 - 61.8	1.046	0.014	0.897	0.240	-0.005
NASA TM	2804	0.008 - 90.0	1.000	0.000	0.892	0.222	-0.000

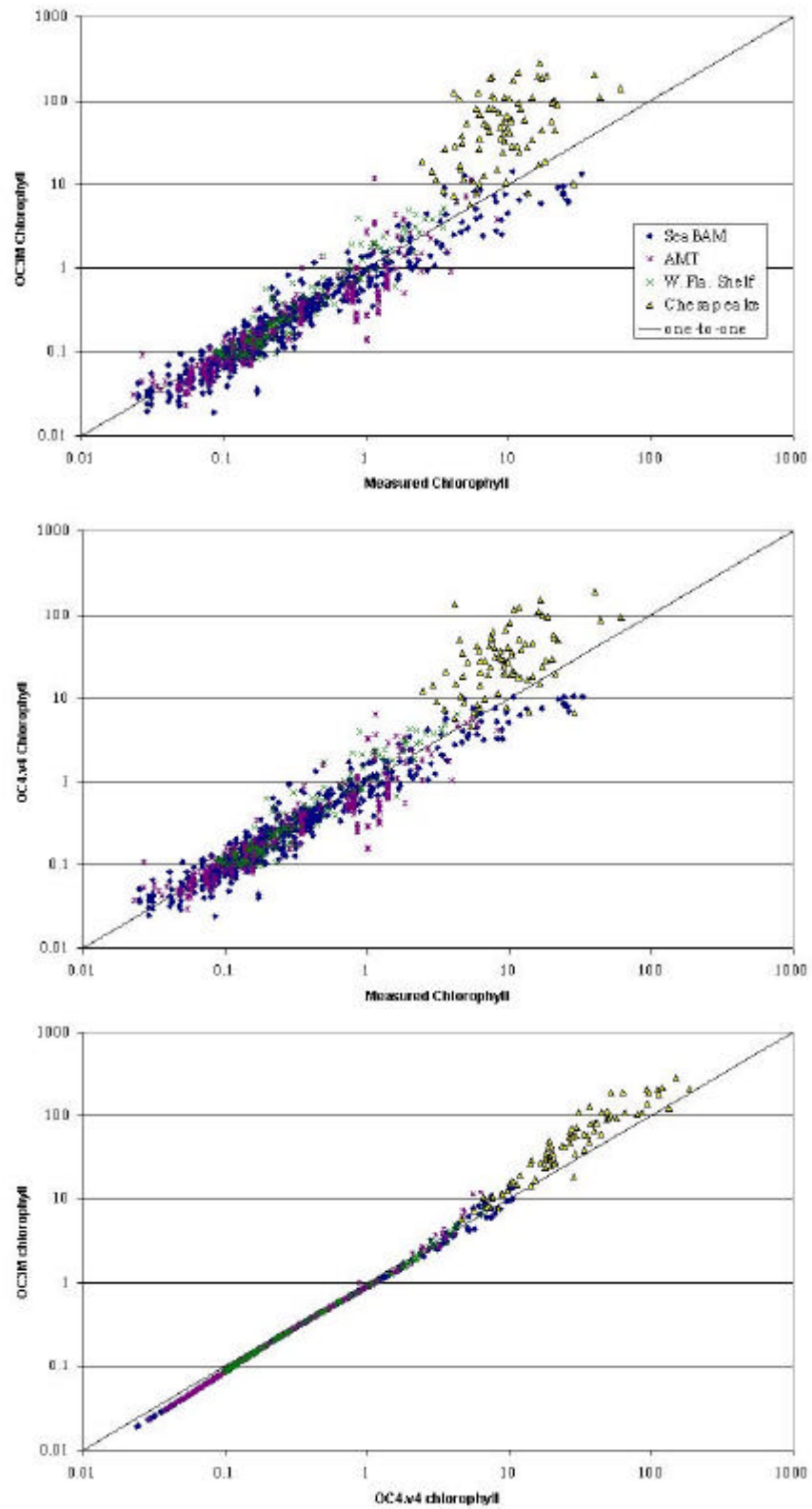


Fig. 2 - Regressions of algorithm-derived chlorophyll concentration vs. measured chlorophyll based on four *in situ* data sets. In the lower panel, the two algorithms are compared with one another.

Both algorithms performed best in the low to medium chlorophyll range ($<1.0 \text{ mg m}^{-3}$), and became systematically worse at higher chlorophyll levels. The Chesapeake Bay data, which is predominately Case 2 waters, yielded the worse results, particularly at high chlorophyll levels where both algorithms overestimated chlorophyll (Fig. 2). Algorithms often overestimate the chlorophyll concentration in Case 2 waters because they attribute all the absorption to the chlorophyll, and do not account for absorption by other organic matter (e.g., CDOM and detritus). It is interesting to note, however, that this was not the case in the SeaBAM data where the algorithms underestimated the high chlorophyll values. In general, the OC3M algorithm tended to underestimate chlorophyll at values below about 1 mg m^{-3} , whereas the OC4.v4 algorithm was unbiased in that range. A possible solution would have been to use the OC4.v4 algorithm coefficients for the MODIS algorithm, thus insuring agreement when the 443 and 488 nm band ratios are used. The lower panel in figure 2 shows how the two algorithms compare with one another. When they are using the same spectral bands, the relationship is deterministic – with OC3M systematically lower than OC4.v4 by 10-20%. When the latter switches to the 510 nm band ratio, the relationship has more random scatter and a tendency for OC3M to exceed OC4.v4. When we evaluated the option of using the OC4.v4 coefficients but not switching to the 510 nm band ratio, the RMS error and bias were 0.354 and 0.045, respectively, both considerably larger than the errors for the OC3M algorithm (Table 1).

- *MODIS vs. SeaWiFS Results.* We evaluated the OC3M algorithm by comparing level-2 scenes from MODIS and SeaWiFS. The scenes, acquired ~100 minutes apart, were co-registered and then chlorophyll images were derived according to the OC3M algorithm (eqs 1 and 2) using MODIS normalized water-leaving radiances at 443, 488, and 551 nm, and SeaWiFS radiances at 443, 490, and 555 nm. Differences were then evaluated between the following: (a) SeaWiFS OC3M vs. SeaWiFS OC4.v4 to compare algorithm differences when applied to the same sensor; (b) SeaWiFS OC3M vs. MODIS OC3M to compare sensor differences for the same algorithm; and (c) SeaWiFS OC4.v4 vs. MODIS OC3M where both algorithms and sensors are different (see example shown in Fig. 3).

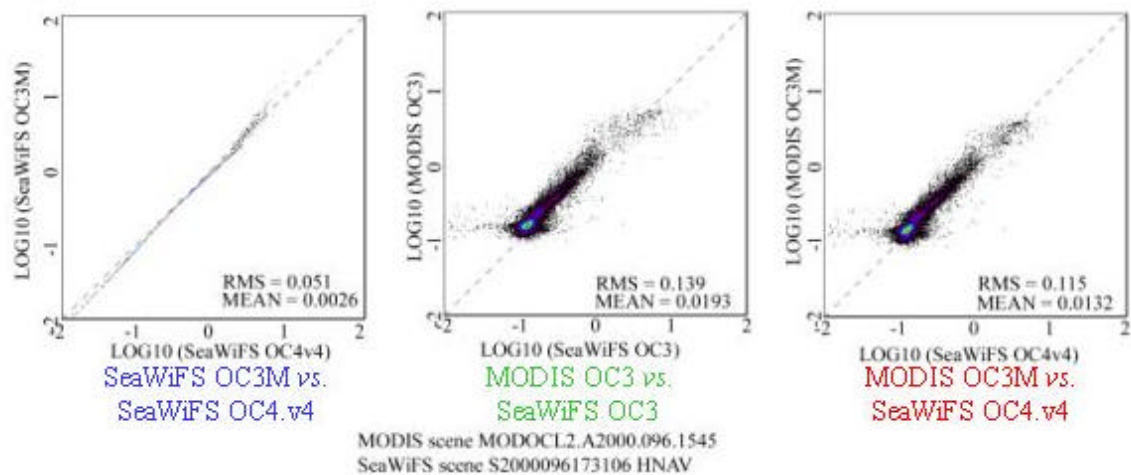


Fig. 3 - Comparison of OC3M and OC4.v4 algorithms when applied to SeaWiFS and MODIS data of the northern Gulf of Mexico on April 7, 2000. On the left, different algorithms are applied to SeaWiFS data (compare with lower panel in figure 2); in the center, the same algorithm is applied to different sensors; and on the right, different algorithms and different sensors are compared.

When the two algorithms were applied to SeaWiFS data (Fig. 3, left panel), patterns were consistent with differences observed in the *in situ* data (Fig. 2, lower panel). All other factors being equal, the OC3M algorithm systematically underestimates the OC4 algorithm in the range of $\text{Chl} < 1 \text{ mg m}^{-3}$. This difference could be eliminated if the same polynomial coefficients were used for both (i.e., replace the coefficients in equation 1 with those for the OC4.v4 algorithm), but apparently the OC3M algorithm yields better results at Chl levels $> 1 \text{ mg m}^{-3}$. The OC3M algorithm applied to SeaWiFS and MODIS data (Fig. 3, middle panel) indicates how differences in the input water-leaving radiances affect the comparisons. In this example, the RMS difference of 0.139 and mean difference of 0.0193 (MODIS minus SeaWiFS; units are decades of log) were actually greater than when the MODIS OC3M was compared with the SeaWiFS OC4, presumably due to offsetting trends. The RMS and mean differences between MODIS OC3M (chlor_a_2) and SeaWiFS OC4.v4 chlorophyll values shown in this example, 0.115 and 0.0132, respectively, were typical. We concluded from this analysis that the two satellite-derived chlorophyll estimates are in closer agreement than either algorithm is to the *in situ* chlorophyll (Table 1). It was decided, therefore, to use the OC3M algorithm for the SeaWiFS-analog chlorophyll algorithm, as it is thoroughly documented in the NASA TM (O'Reilly *et al.* 2000).

The OC3M algorithm has been implemented in MODIS's Collections 3 and 4 processing, and the results have been validated as being consistent with SeaWiFS chlorophyll (Fig. 4). The three empirical algorithms (chlor_MODIS, chlor_a_2, and OC4.v4) are all much more alike than the semi-analytical algorithm (chlor_a_3) to any other.

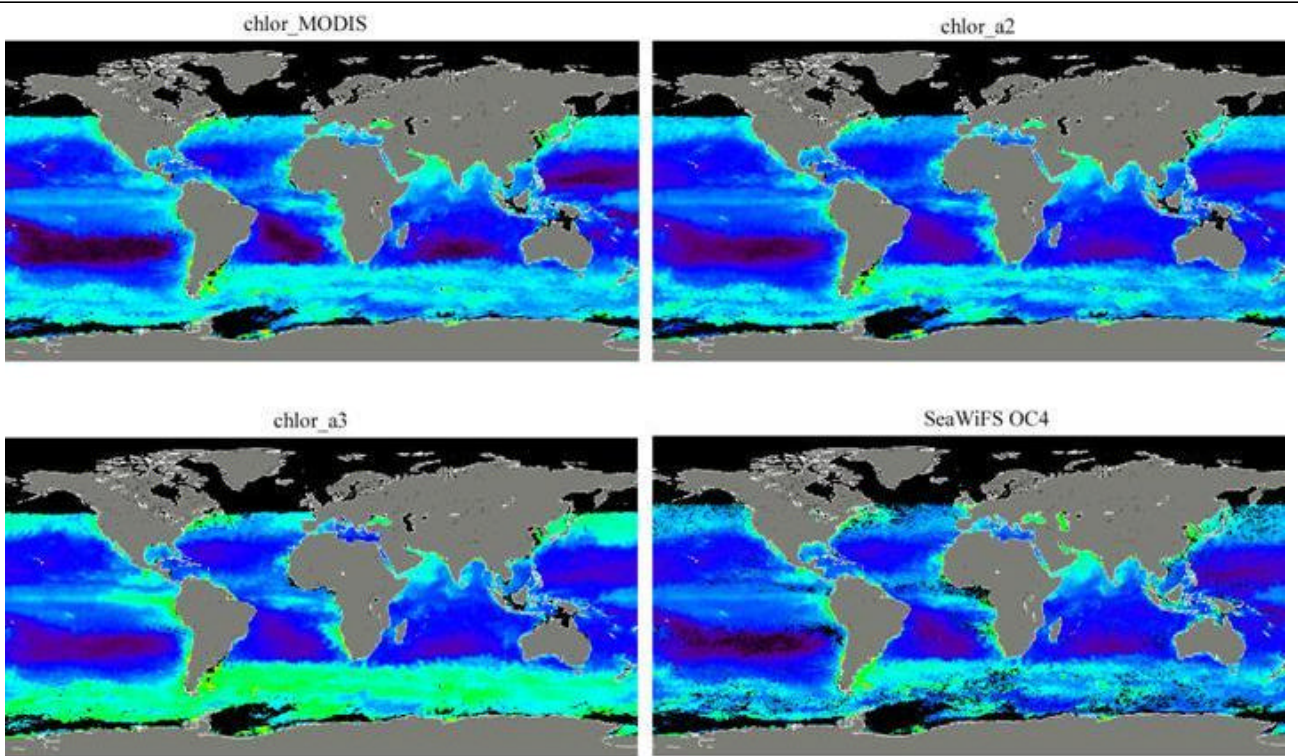


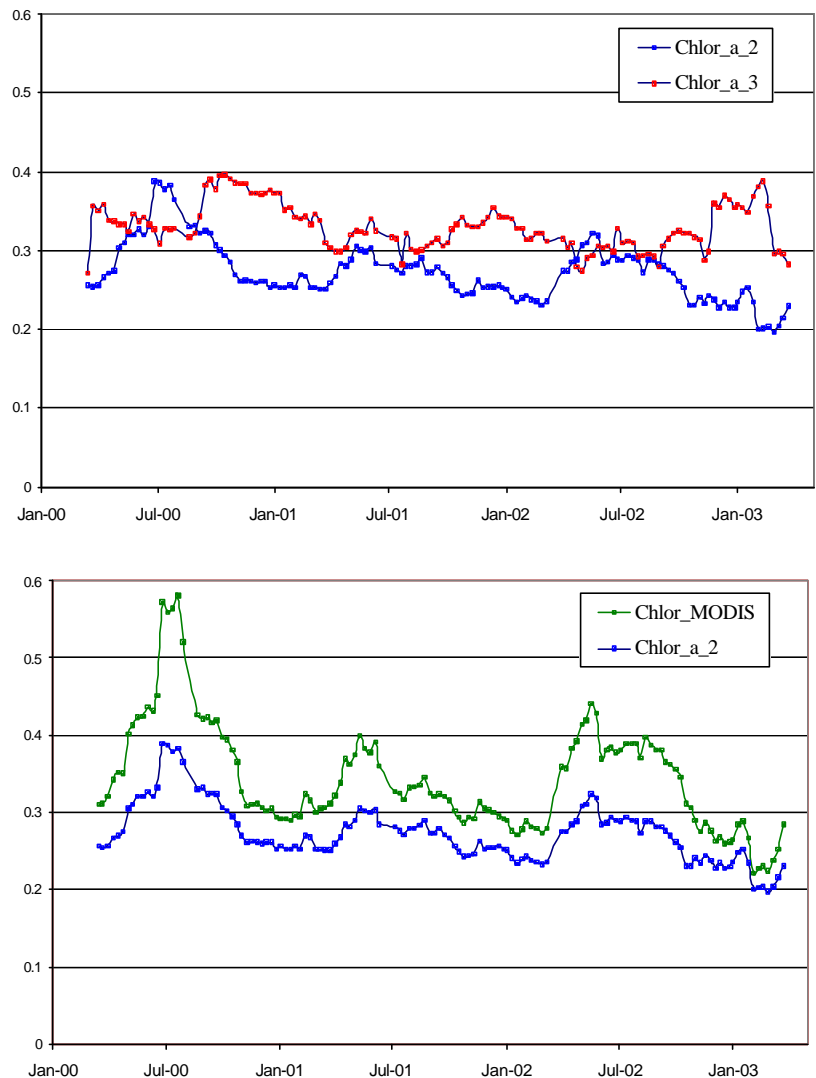
Fig. 4 Comparison of three MODIS Chlorophyll Products and SeaWiFS Chlorophyll in December 2000. Data are monthly averages based on Collection 4 processing and SeaWiFS 4th reprocessing.

Chlor_a_3 is especially different from the other algorithms in the Southern Ocean. Comparisons made with *in situ* data from this region indicate that the semi-analytical algorithm performs better there (Carder *et al.* 2003). The Carder algorithm utilizes a lower chlorophyll-specific absorption coefficient (a_{ph}^*) in the Southern Ocean which is attributed to highly packaged cells in nutrient replete conditions. The low water temperatures are well below the nitrate depletion temperature (NDT, Kamykowski *et al.* 2002), as nitrate is in ample supply. However, these waters are considered to be nutrient limited for lack of sufficient iron (Martin *et al.* 1990). The low a_{ph}^* may be due to other factors such as a larger mean cell size (absence of picoplankton and prochlorophytes), abundance of photo-protective pigments, and other reasons (Reynolds *et al.* 2001, Moisen and Mitchell, 1999).

Time series of the three global chlorophylls are shown in figure 5. The global mean chlor_a_2 (blue) is often lower than the chlor_a_3 (red curve). The largest differences occur during the austral summer when the Southern Ocean is in full sunlight.

Chlor_a_2 and chlor_MODIS time series are similar (lower panel). This is not surprising since they both involve blue-green band ratios but different coefficients. The ratio of the mean chlor_MODIS to the mean chlor_a_2 ranges from 1.1 to 1.5.

Fig. 5. Weekly mean global chlorophylls. Data are from the MODIS quality assurance website: <http://mqabi.gsfc.nasa.gov/>



Protocols for Blending Case 2 Algorithms

The strategy for this work has been to promote the use of a standard semi-analytic remote-sensing reflectance model that relates remote-sensing reflectance to inherent optical properties (absorption and backscattering coefficients), and then to prescribe methods for parameterizing the IOPs as functions of the constituent concentrations of interest (chlorophyll, colored dissolved organic matter, and suspended sediment). This work requires complete in-situ data sets of the apparent and inherent optical properties, as well as the variables to be retrieved (chlorophyll, CDOM, suspended sediment).

It is our belief that model-based (“semi-analytic”) bio-optical algorithms will be regionally specific to account for differences in the optical properties of materials in the water. Our approach calls for a set of algorithms parameterized for distinct bio-optical provinces. Unlike the provinces of Carder’s algorithm, which are based on SST distributions, ours are based on the reflectance spectra in the visible-wavelength bands of SeaWiFS or MODIS. Six distinct bio-optical provinces have been identified from *in situ* data and mapped globally using satellite ocean color data. The six bio-optical classes were identified by applying a fuzzy c-means cluster analysis to a globally distributed *in situ* data set of over 1,700 reflectance measurements. Four of the classes are oceanic and exhibit optical properties in accordance with Case 1 optical models. The two remaining classes represent CDOM-dominated and sediment-dominated Case 2 waters. The six provinces are considered adequate to describe the variability in optical properties globally and, in the Case 1 classes, are believed to represent distinct assemblages of phytoplankton. Our approach, originally described in Moore et al. (2001), is to use fuzzy membership functions to select and blend bio-optical algorithms thus allowing for smooth transitions across ocean water boundaries. Semi-analytical algorithms are now being developed for each of these classes using the *in situ* data described above.

We hypothesize that the bio-optical provinces correspond to phytoplankton assemblages with varying degrees of packaging. Two of the classes are found in the Southern Ocean, and in coastal upwelling areas. In figure 6, we show the fuzzy membership functions for the four Case 1 classes determined using MODIS radiance data for December 2000. A fuzzy membership function assigns class memberships to all pixels in a satellite image based on class-specific reflectance statistics derived from the *in situ* data. The membership function returns a value ranging from 0 to 1 for each pre-defined class, and allows each pixel to have partial class membership to one or more classes. The class membership values can be used to weight and blend the class-specific algorithm retrievals of chlorophyll a, colored dissolved organic matter absorption, and particle backscattering.

In our future work, as members of the MODIS team, we propose to apply this method to MODIS data to blend semi-analytical chlorophyll retrievals, and compare results with the standard semi-analytical chlorophyll (“chlora_3”) of Carder et al. (1999) as currently implemented in the MODIS software (now available from the NASA Goddard Direct Readout Portal). We will experiment with the various parameter sets used by the Carder model to determine which ones are associated with the various bio-optical provinces.

**Class 1:
Super
oligotrophic**

**Class 2:
Oligotrophic**

**Class 3:
Mesotrophic**

**Class 4:
Eutrophic**

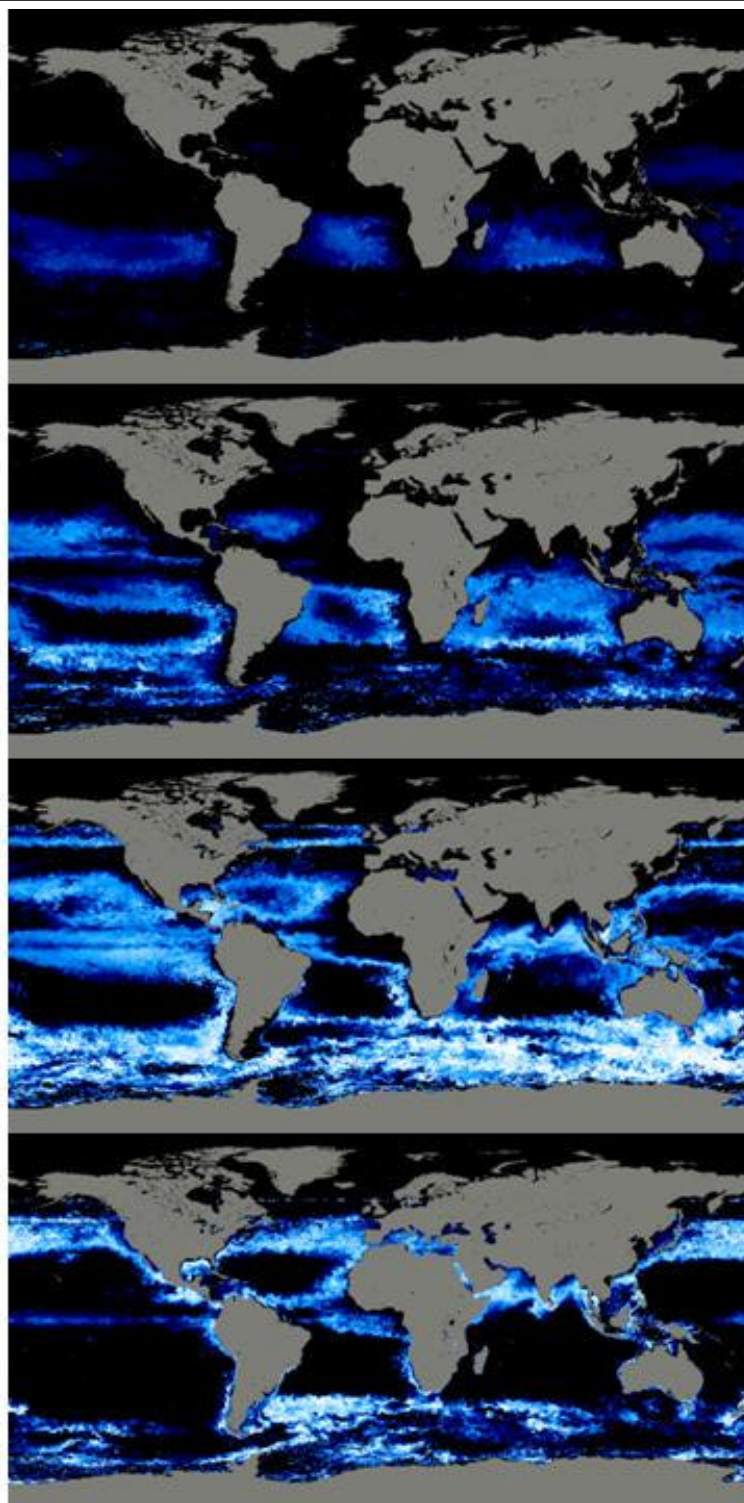


Fig. 6 – Membership maps for the four Case 1 bio-optical provinces derived from MODIS water-leaving radiances in December 2000. These membership values (ranging from 0 to 1) can be used to blend bio-optical algorithms for each of the classes.

Primary productivity algorithms

One of the initial tasks supported by this MODIS contract was to complete the analysis and documentation of a “round robin” experiment designed to compare primary productivity algorithms. The round robin experiments began in 1994 under the auspices of NASA’s Primary Productivity Science Working Group chaired by Paul Falkowski and Wayne Esaias. The first experiment involved comparisons of algorithm results with measured primary productivity at 25 stations. It was later decided that there were too few stations, and so the second Primary Productivity Round Robin Experiment (PPARR2) was initiated in 1996 with 89 stations.

A manuscript describing this second experiment has been completed and published (*Global Biogeochem. Cycles*, 16(3), 10.1029 / 2001GB001444, 2002). Following is the title, authors, and abstract of that paper:

COMPARISON OF ALGORITHMS FOR ESTIMATING OCEAN PRIMARY PRODUCTION FROM SURFACE CHLOROPHYLL, TEMPERATURE AND IRRADIANCE

Janet Campbell, David Antoine, Robert Armstrong, Kevin Arrigo, William Balch,
Richard Barber, Michael Behrenfeld, Robert Bidigare, James Bishop, Mary-Elena Carr,
Wayne Esaias, Paul Falkowski, Nicolas Hoepffner, Richard Iverson, Dale Kiefer, Steven
Lohrenz, John Marra, Andre Morel, John Ryan, Vladimir Vedernikov, Kirk Waters,
Charles Yentsch, and James Yoder

Abstract

Results of a single-blind round-robin comparison of satellite primary productivity algorithms are presented. The goal of the round-robin exercise was to determine the accuracy of the algorithms in predicting depth-integrated primary production from information amenable to remote sensing. Twelve algorithms, developed by ten teams, were evaluated by comparing their ability to estimate depth-integrated daily production (IP, mg C m^{-2}) at 89 stations in geographically diverse oceanic provinces. Algorithms were furnished information about the surface chlorophyll concentration, temperature, photosynthetic available radiation, latitude, longitude, and day of the year. Algorithm-derived estimates of IP were then compared with estimates derived from ^{14}C uptake measurements at the same stations. Estimates from the best-performing algorithms were generally within a factor of two of the ^{14}C -derived estimates, which varied by two orders of magnitude in the test data set. This level of agreement is comparable to that reported for chlorophyll algorithms (O’Reilly et al., 1998). Many algorithms had systematic biases which can possibly be eliminated by re-parameterizing underlying relationships between productivity, light, and temperature. The performance of the algorithms was independent of their complexity, and results from different algorithms were often highly correlated.

In March 2000, Dr. Mark Dowell joined my team as a staff scientist. Mark received a Ph.D. in oceanography from Southampton University in 1998, where his dissertation was on “Optical characterization and reflectance modeling in Case 2 water: quantitative tools for investigations of coastal environments.” Mark had been active in bio-optical algorithm

development in Europe, and he brought with him an extensive data set of measurements made in European coastal waters. Mark worked on the development of a coastal primary productivity algorithm under this contract. His primary focus was on parameterizing the photosynthetically useable radiation (PUR) in Case 2 waters where substances other than phytoplankton absorb the photosynthetically available radiation (PAR).

Mark Dowell worked on an algorithm for computing primary production in coastal waters based on a wavelength-resolved model of photosynthetically usable radiation (PUR). This required a formulation of the diffuse attenuation coefficient (K_d) to account for the optically complex characteristics of coastal waters as well as a parameterization of a geometric correction factor “g” to convert vector irradiance into scalar irradiance (highly significant in turbid coastal waters). A preliminary sensitivity analysis has shown that the influence of the coastal water IOPs is critical at various stage of the primary production calculation. This was shown firstly in the calculation of the euphotic depth (Z_{eu}), where depths calculated based on a Case 1 type model were typically between 50-100% higher than those calculated by a more appropriate Case 2 model. Similarly, when calculating primary production through a depth-integrated model, such as that adopted for operational processing by the MODIS project, it was found that a Case 1 model resulted in a 30-70% over-estimation of the integrated primary production as compared with a Case 2 model. Significantly it was also shown that the IOPs of Case 2 water had a significant effect on the spectral quality of the available and usable light for photosynthesis.

The model parameterized based on Case 2 IOPs provides a PUR product which can be used with a coastal a_{ph} model and the light utilization index (ψ^*) to calculate the depth integrated primary production. Different solutions were considered to retrieve ψ^* in these regions, one of which would use fuzzy methods to classify the coastal water mass based on information pertaining to chlorophyll, SST, PAR, and daylength. To this end, we identified 9 distinct classes or regimes using the primary productivity data base of Behrenfeld and Falkowski (<http://marine.rutgers.edu/opp>) augmented with primary productivity measurements at 85 coastal stations. The next step was to determine a model of ψ^* for each class. Thus when a satellite image is processed, the fuzzy memberships can be calculated based on the end-member ψ^* value for each class resulting in a map of the geographic distribution of ψ^* . To merge this and the other two existing MODIS primary production products into a single global PP map, the application of fuzzy logic techniques was to be taken one step further. We evaluated the performance of each of the proposed algorithms in different global predetermined classes (resulting from the classification of the large global PP data sets of Falkowski and Behrehfeld). The validation exercise for each class, however, used an independent data set not used in any of the algorithm development processes. Thus the performance of each algorithm was evaluated in each class and a best candidate selected. At the time of this report, Mark Dowell is participating in the third Primary Productivity Algorithm Round Robin (PPARR3) that is being conducted by Mary-Elena Carr (JPL). The primary productivity algorithm development work by Mark Dowell has not yet been published.

My graduate student (Seung-Hyun Son) spent two months at the Bedford Institute of Oceanography, Halifax, Nova Scotia, in 2003 working under the supervision of Dr. Shubha Sathyendraneth. This trip was supported by a fellowship from the International Ocean Colour Coordinating Group (IOCCG). He has produced primary productivity maps of the

Yellow and East China Seas using MODIS chlorophyll and SST data. This will be part of his dissertation.

Demonstration in Gulf of Maine and Yellow Sea Regions

We have assembled a database of in-situ bio-optical data for the two demonstration sites: Gulf of Maine and Yellow Sea.

- Gulf of Maine. We have received a shipment of all the MODIS Collection 4.0 granules for the northwest Atlantic Continental Shelf (between Nova Scotia and Cape Hatteras, NC). We have remapped all the granules to provide daily images, and then formed weekly (8-day) averages. These data are being served by WebCOAST, a web-based data and information server funded by NOAA as one of the projects supported by the Center of Excellence for Coastal Observation and Analysis (COOA). Currently WebCoast is serving remapped chlorophyll and SST data, as well as other products. We post 8-day browse images on WebCOAST, but all the data are available via ftp or other media. Other details of our plans are described in our January 2003 report. In addition, Mark Dowell has begun a series of monthly cruises to gather bio-optical and primary productivity data for parameterizing algorithms. These cruises are supported by the COOA center.

In collaboration with Mark Dowell, Ru Morrison, and Heidi Sosik, we have made monthly cruises funded by the University of New Hampshire (UNH) center of excellence in Coastal Ocean Observation and Analysis (COOA). The measurements made include chlorophyll, AOPs and IOPs, as well as other physical and chemical properties. We have conducted monthly cruises in the Gulf of Maine beginning in April 2003, and 3-day cruises will take place in the summer of 2004 in the vicinity of the

Martha's Vineyard Coastal Observatory (MVCO). All suitable measurements will be submitted to the NASA SeaBASS database for archiving and distribution. In addition, we are cooperating with the Gulf of Maine Ocean Observing System (GoMOOS) to compare MODIS data with measurements made at GoMOOS buoys. Further information can be found at: <http://www.cooa.unh.edu/>.

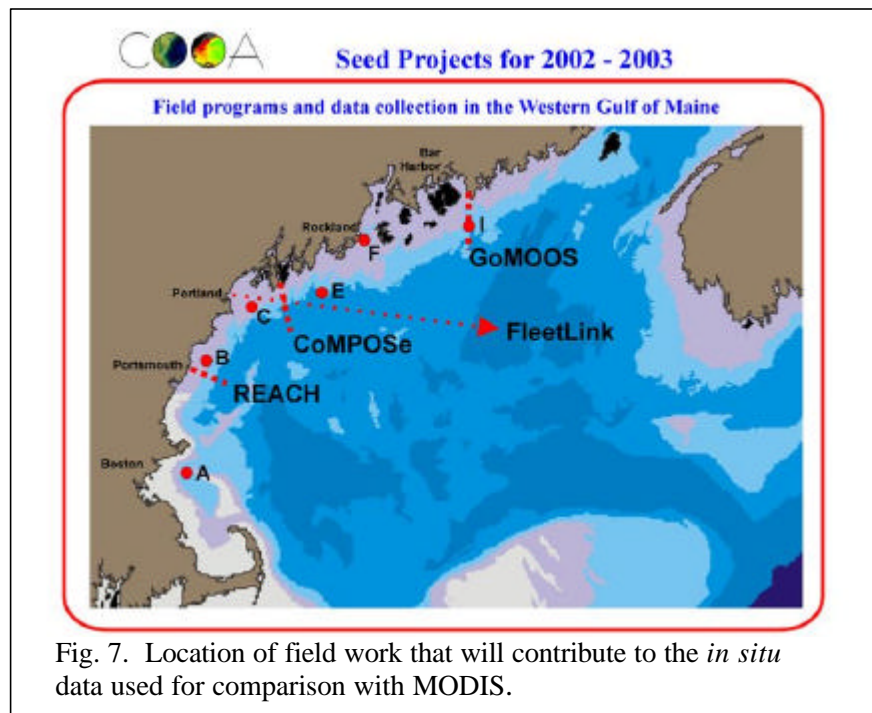


Fig. 7. Location of field work that will contribute to the *in situ* data used for comparison with MODIS.

- Yellow and East China Seas. This is the thesis work of Seung-Hyun Son, who expects to complete his Ph.D. dissertation in late 2003. He has compared fronts visible in MODIS SST and chlorophyll data to the Simpson-Hunter H/U^3 criterion for mixed versus stratified waters. The latter was derived using a wind-wave model (Moon, 2000 thesis) and bathymetry data. His goal was to use MODIS data to differentiate stratified and well-mixed regions during the periods of seasonal stratification. This will later be used to model the vertical distribution of chlorophyll and other optically active constituents in development of a primary productivity model for this region. A poster on this work was presented at the XVII Ocean Optics Conference in November 2002, and at the MODIS Ocean Data Products Workshop at UNH in February 2003. At the Bedford Institute of Oceanography in summer 2003, he parameterized primary productivity algorithms using a database of P-I model parameters, and vertical profiles of chlorophyll and light.

Development of Monitoring Strategies

MODIS data are and will continue to be a major resource for the UNH Center of Excellence for Coastal Ocean Observation and Analysis (COOA). The primary mission of COOA is to develop and implement new tools for monitoring coastal marine ecosystems. This is ongoing work, and will become an integral part of future MODIS activities.

Support of MODIS Ocean Team Activities

For the past several years, we been active in the evaluation and validation of MODIS products in support of new codes applied to the forward processing and the reprocessing. The new codes were put into operation in June 2002. The MODIS Oceans Team has held weekly teleconferences to discuss issues raised during this phase. We have continued to evaluate MODIS chlorophyll products and compare them with SeaWiFS chlorophyll data acquired at the same location and on the same day. Comparisons were presented at MODIS Science Team meetings, most recently at the meeting in Greenbelt, Maryland, in July 2002. We concluded that the Chlor_{a2} product for the period November 1, 2000 to March 19, 2002 was validated based on its agreement with the SeaWiFS chlorophyll product. I have proposed (and been accepted) to continue on the MODIS science team as the member responsible for the Chlor_{as} “SeaWiFS analog” chlorophyl product.

In 2002-2003, I took responsibility for a major re-writing of the EOS Data Handbook sections involving MODIS Ocean Data Products. The previous edition had been published long before MODIS was launched (even before SeaWiFS was launched), and thus the Handbook needed substantial editing.

I organized the first regional MODIS Ocean Data Products Workshop which was held at the University of New Hampshire on February 3-4, 2003. This workshop provided a comprehensive summary of the status of the MODIS Ocean data products to an audience of 70 people (50% from New England, but others from as far away as Germany, England, The Netherlands, Canada, Puerto Rico, and California). Most of the audience were from academic institutions, but there were representatives from private industry and government laboratories as well. Members of the MODIS Ocean Science team and the Goddard DAAC covered step-by-step details of the processing, distribution, analysis, and interpretation of the MODIS Ocean variables. The workshop also included a hands-on

computer tutorial that took participants through details of data ordering, reprojection, reformatting and other technical tools. This provided a forum for team members to present information about MODIS data products (including new products introduced by the new Science Team). A website (<http://www.opal.sr.unh.edu/modisworkshop>) was developed for the workshop that was effective in publicizing the workshop and subsequently providing logistical information for attendees.

In October, 2002, I co-chaired the session on “Biological and Physical Oceanographic Processes from Satellite Data” at the World Space Congress 2002 in Houston, Texas, October 17-18, 2002. I solicited invited papers from among the MODIS Oceans Team. Ken Carder presented an invited paper which was subsequently submitted to the *Advances in Space Research*. Mark Dowell also presented his results related to the primary productivity algorithm development. I subsequently served as associate editor for this journal for the publication of papers in the realm of biological oceanographic processes. The issue containing these papers still has not been published as far as I know.

Accomplishments in Related Areas

With funding from NASA’s Ocean Biology / Biogeochemistry Program (NAG5-11258), Amala Mahadevan and I have developed a simple technique for characterizing scales of variability in surface waters. The aim of this work was to characterize the spatial distributions of various tracers in terms of a variance-based measure of their patchiness. Using a scaling argument and a numerical model, we related the patchiness of a tracer distribution to the characteristic response time of the tracer to processes that alter its concentration in the upper ocean. This enables us to relate the distributions of different tracers in the upper ocean and provide an estimate for the relative size of the grid spacing needed to observe or model different tracers. We applied this method to MODIS chlorophyll and SST data. The MODIS data are particularly suited to this analysis because of the simultaneous acquisition of both SST and chlorophyll. Previously we applied it to SeaWiFS and AVHRR data acquired on the same day at the same place, but the time differences between the two satellite overpasses made direct comparisons much more difficult. The work has appeared in two publications (Mahadevan and Campbell, 2002 and 2003).

As a member of an IOCCG working group, I participated in writing a report on binning algorithms. In my contribution to this report, I demonstrated how various averaging methods introduce systematic differences in level-3 (binned) data products. In addition, I explored an issue related to the time scale of the input data used in producing primary productivity (level-4) products. In that section, I showed that the monthly average primary productivity (PP) generated from daily input (PPd) differs from that derived by using monthly averaged input fields (PPm). I compared two algorithms: the Behrenfeld and Falkowski algorithm used by MODIS to generate the P1 product, and a modified version of the Howard-Yoder-Ryan algorithm used to generate the MODIS P2 product. The latter was modified to estimate euphotic rather than mixed-layer PP. It is generally believed that it is preferable to apply a nonlinear equation to daily input fields and then average the result, rather than use monthly average input fields. However, in the case of PP algorithms, when this is done, there is a clear-sky bias. That is, PPd is calculated only where there are chlorophyll and SST measurements, i.e., clear-sky conditions. The PAR fields are not affected by clouds since there is PAR beneath clouds. Using monthly input fields to derive

PP, one can use the average PAR based on all pixels (both cloudy and clear). A good compromise is to derive PP from weekly average input fields as is done with MODIS.

The MODIS data have several major advantages over SeaWiFS. One is the fact that MODIS provides simultaneous SST and chlorophyll. These are two properties often used as input to primary productivity algorithms. It is difficult to match SST and chlorophyll derived from different satellites (e.g., SeaWiFS and AVHRR) because of differences in the cloud masks. Another advantage of the MODIS is its daily coverage. The time rate of change of algal biomass (dB/dt) can be used, together with estimates of primary production, to estimate the loss rate (due to sinking or grazing by zooplankton). To date a major obstacle in using satellite data to study these loss terms at global scale has been that the time step (dt) has been too large (i.e., typical cloud-free global coverage on the order of 30 days). With the advent of the MODIS sensor which provides almost perfect cloud-free coverage of the global ocean within a 7 day period, a more relevant dataset for studying phytoplankton loss terms now exists. Mark Dowell presented a poster on this at the IGBP Oceans Conference in Paris in January 2003. This poster was also displayed at the MODIS Oceans Data Products Workshop in February 2003.

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APPENDIX: PUBLICATIONS AND PRESENTATIONS

(a) *Refereed Journal Articles*

- Salisbury, J. E., J. W. Campbell, E. Linder, L. D. Meeker, F.E. Muller-Karger, and C.J. Vorosmarty, On the seasonal correlation of surface particle fields with wind stress and Mississippi River discharge in the Northern Gulf of Mexico. (submitted July 2002, revised September, 2003).
- Carder, K. L., F.R. Chen, J.P. Cannizzaro, and J.W. Campbell. "Performance of MODIS Semi-analytic Ocean Color Algorithm for Chlorophyll-a." (in press, *Adv. Space Res.*, Apr. 2003)
- Campbell, J.W., D. Antoine, R. Armstrong, K. Arrigo, W. Balch, R. Barber, M. Behrenfeld, R. Bidigare, J. Bishop, M.-E. Carr, W. Esaias, P. Falkowski, N. Hoepffner, R. Iverson, D. Kiefer, S. Lohrenz, J. Marra, A. Morel, J. Ryan, V. Vedernikov, K. Waters, C. Yentsch, and J. Yoder. Comparison of algorithms for estimating ocean primary productivity from surface chlorophyll, temperature, and irradiance. *Global Biogeochem. Cycles*, **16**(3), 10.1029 / 2001GB001444, 2002.
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(b) *Book Chapters and Monographs*

- IOCCG Working Group on Ocean Color Data Binning Issues, Guide to the Use and Creation of Ocean Color Level-3 Data, D. Antoine (ed.), In press 2004
- Mahadevan, A. and J. W. Campbell. Biogeochemical Variability at the Sea Surface: How it is linked to process response times. In: *Scales in Ecology*, Laurent Seuront (ed.), CRC Press, 2003.
- Parslow, J., N. Hoepffner, R. Doerffer, J. Campbell, and S. Sathyendranath. Chapter 5. Case 2 Ocean-Colour Applications. In: *Remote Sensing of Ocean Colour in Coastal and other Optically Complex Waters*, S. Sathyendranath (ed.), Report 3, International Ocean Colour Coordinating Group, pp. 94-116, 2000.

(c) *Other Publications*

- Liu, A.K., Y. Zhao, W.E. Esaias, J. W. Campbell, T. S. Moore. Ocean Surface Layer Drift Revealed by Satellite Data. *EOS Transactions*, American Geophysical Union, **83** (7), Feb. 12, 2002, 61-64.
- J. E. Salisbury, J. W. Campbell, L. D. Meeker, and C.J. Vorosmarty, Ocean Color and River Data Reveal Fluvial Influence in Coastal Waters, *EOS Transactions*, American Geophysical Union, **82** (20), May 15, 2001.
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(d) *Invited presentations*

- Campbell, J.W. The role of satellites in monitoring water quality: Addressing goals of the 2000 Chesapeake Bay Agreement. Workshop on Applications of Remote Sensing and In-situ Sensors, Maryland Sea Grant, January 7-8, 2002.
- Campbell, J.W. The Potential Application of MODIS to Coastal Monitoring. EMAP Symposium 2001: Coastal Monitoring through Partnerships, St. Petersburg, FL, April 2001.
- Campbell, J.W. Satellite-based estimation of marine primary production: current status and future directions. JGOFS Global Synthesis Task Team Meeting, Amsterdam, July 2001.
- Moore, T.S., M.A. Dowell, and J.W. Campbell. Bio-Optical Provinces in the World's Oceans Based on a Fuzzy Classification of Satellite Ocean Color Data. Oceanography from Space Conference, Venice, Oct. 2000.
- Campbell, J.W. Status of NASA's Ocean Biology and Biogeochemistry Program, Pacific Ocean Remote Sensing Conference, Qingdao, China, August 1998.
- Campbell, J.W. New Era of Ocean Color Remote Sensing. Keynote address, Fifth International Conference on Remote Sensing for Marine and Coastal Applications, San Diego, CA, October 1998.

Campbell, J.W. Primary Productivity Round Robin Experiments. Japan-United States Workshop on Ocean Color, Atami, Japan, March 1997.

(e) Contributed presentations

Son, Seung-Hyun, Janet Campbell, Mark Dowell, and Timothy Moore. Decadal and Inter-annual Variations in the Yellow and East China Seas Revealed by Satellite Ocean Color Data (1979-2002). Poster presented at the JGOFS Open Science Conference, Washington, DC, May 2003. (This poster won the Best Student Poster in its category).

Son, Seung-Hyun, Janet W. Campbell, Mark D. Dowell, Il-Ju Moon, and Sinjae Yoo. Classification of Well Mixed and Stratified Waters in the Yellow and East China Seas. Poster presented at the Ocean Color Science Team Meeting, Miami, April 2003.

Dowell, Mark D., Jeffrey Runge, and Janet Campbell. Characterizing the global distribution and nature of the rate of algal loss in pelagic marine ecosystems. Poster presented at the IGBP Oceans Conference, Paris, France, January 2003; and at the Ocean Color Science Team Meeting, Miami, April 2003.

Christopher Wason, Matt Giguere, Maeghen Driscoll, Lisa Seydewitz, Dan Hocking, Erin Faltin John Baker, Michael Novak, Shane Bradt, Janet Campbell, Richard Blakemore, Alan Baker. Project Lake Watch: On Golden Pond for Lake Truthing Landsat and MODIS. This was one of three posters presented at the ASLO Aquatic Sciences Conference, Salt Lake City, Utah, February 2003. This poster won a blue ribbon for merit in the student poster competition.

Mahadevan. A and J. Campbell. Biogeochemical patchiness at the sea surface. Ocean Sciences Meeting, Honolulu, February 2002.

Dowell, M., J. Campbell and T. Moore. Dynamic ecological provinces: A biogeochemical and physiological template for the global ocean, JGOFS Conference on Global Ocean Productivity and the Fluxes of Carbon and Nutrients: Combining Observations and Models. JRC Ispra, Italy, June, 2002.

Dowell, M., T. Moore, and J. Campbell. Dynamic Ecological Provinces: An Objective Bio-Geography Based on Global Satellite Data. IGBP Meeting on the Challenges of a Changing Earth, Amsterdam NL, July, 2001.

Campbell, J. W. , T. Moore, and H. Feng. Fuzzy logic applied to coastal ocean remote sensing. Sixth International Conference on Coastal and Marine Remote Sensing, Charleston, SC, May 2000.

Campbell, J.W. The primary productivity algorithm round robin experiments: progress report and future plans. SeaWiFS Science Team Meeting, Durham NH, May 2000.

Campbell, J.W. Selecting algorithms and blending retrievals in coastal waters. MODIS Science Team Meeting, College Park, MD, June 2000.

- Dowell, M.D., J.W. Campbell, and N. Hoepffner. Primary production modeling in Case II waters: Implications of the parameterization of photosynthetically usable radiation (PUR). Oceanography from Space Conference, Venice, October 2000.
- Campbell, J.W., T. S. Moore, and W. M. Balch. Dynamic patterns of particle backscatter in the ocean. Ocean Optics XV Conference, Monaco, October 2000.
- Moore, T. S., M. D. Dowell, J.W. Campbell and N. Hoepffner. Universally Tailored Optical Parameter Inversion Algorithm (UTOPIA) I: Global Classification. Ocean Optics XV Conference, Monaco, October 2000.
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